

# Neutrino Mass from Triplet and Doublet Scalars at the TeV Scale

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## Abstract

If the minimal standard model of particle interactions is extended to include a scalar triplet with lepton number  $L = -2$  and a scalar doublet with  $L = -1$ , neutrino masses  $m_\nu \sim \mu_{12}^4 v^2 / M^5 \sim 10^{-2}$  eV is possible, where  $v \sim 10^2$  GeV is the electroweak symmetry breaking scale,  $M \sim 1$  TeV is the typical mass of the new scalars, and  $\mu_{12} \sim 1$  GeV is a soft lepton-number-violating parameter.

In the minimal standard model of particle interactions, neutrinos are massless, but if new interactions exist at a higher scale, then they may become massive through the unique effective dimension-five operator [1]

$$\mathcal{L}_{eff} = \frac{f_{ij}}{\Lambda} L_i L_j \Phi \Phi, \quad (1)$$

where  $L_i = (\nu_i, l_i)_L$  is the usual left-handed lepton doublet,  $\Phi = (\phi^+, \phi^0)$  is the usual scalar Higgs doublet, and  $\Lambda$  is an effective large mass. There are three tree-level realizations [2] of this operator: (I) the canonical seesaw mechanism [3] using one heavy right-handed neutrino  $N_R$  for each  $\nu_i$ ; (II) the addition of a heavy Higgs triplet  $(\xi^{++}, \xi^+, \xi^0)$  which couples to  $L_i L_j$  directly [4, 5]; and (III) the replacement of  $N_R$  with  $(\Sigma^+, \Sigma^0, \Sigma^-)_R$  [6, 7]. If the mass of  $N$  or  $\xi$  or  $\Sigma$  is very large, then each realization is the same as any other at low energies, because the only observable effect would be the appearance of small Majorana neutrino masses.

It has recently been pointed out that simple extensions of the above minimal scenarios for neutrino mass are possible for which the scale of new physics may be only a few TeV and thus be observable at future accelerators. There are two specific proposals: (A) the Higgs triplet  $\xi$  may be only a few TeV, whose decay into two leptons would map out all elements of the neutrino mass matrix [8]; and (B) the fermion singlets  $N_R$  as well as a second Higgs doublet  $\eta = (\eta^+, \eta^0)$  may be only a few TeV [9].

In (A), the notion of lepton-number violation as a distance effect from the separation of our brane from another in the context of large extra dimensions is invoked to explain the smallness of the trilinear scalar coupling of  $\xi$  to  $\Phi\Phi$ . In (B), there is no need to consider large extra dimensions. Instead, the effective operator of Eq. (1) is suppressed because  $\Phi$  is replaced with  $\eta$ , which has a naturally small vacuum expectation value. In this note, the two mechanisms are synthesized so that there is a Higgs triplet  $\xi$  from (A), and a Higgs doublet  $\eta$  from (B), but no  $N_R$ . Neutrino masses come from  $\xi$  (which is assigned lepton number  $L = -2$ ), and its interaction with  $\eta$  (which has  $L = -1$ ). The smallness of  $m_\nu$  comes from

the soft breaking of  $L$  in the scalar sector, with the result

$$m_\nu \sim \frac{\mu_{12}^4 v^2}{M^5} \sim 10^{-2} \text{ eV}, \quad (2)$$

where  $v \sim 10^2 \text{ GeV}$  is the electroweak symmetry breaking scale,  $M \sim 1 \text{ TeV}$  is the typical mass of the new scalars, and  $\mu_{12} \sim 1 \text{ GeV}$  is a soft lepton-number-violating parameter. This model requires neither large extra dimensions nor  $N_R$  to obtain naturally small Majorana neutrino masses, and have verifiable experimental consequences at the TeV scale.

In the Higgs triplet model,  $\xi$  couples to leptons according to

$$\mathcal{L}_Y = f_{ij}[\xi^0 \nu_i \nu_j + \xi^+(\nu_i l_j + l_i \nu_j)/\sqrt{2} + \xi^{++} l_i l_j] + H.c., \quad (3)$$

resulting in  $(m_\nu)_{ij} = 2f_{ij}\langle\xi^0\rangle$ . Therefore, in order to explain why neutrino masses are so small, a natural mechanism for  $\langle\xi^0\rangle$  to be small is needed. Consider now the Higgs sector consisting of the usual standard-model doublet  $\Phi$  (with  $L = 0$ ), a second doublet  $\eta$  (with  $L = -1$ ), and a triplet  $\xi$  (with  $L = -2$ ). Let

$$\Delta \equiv \begin{pmatrix} \xi^+/\sqrt{2} & \xi^{++} \\ \xi^0 & -\xi^+/\sqrt{2} \end{pmatrix}, \quad (4)$$

then the most general  $L$ -conserving Higgs potential is given by

$$\begin{aligned} V = & m_1^2 \Phi^\dagger \Phi + m_2^2 \eta^\dagger \eta + m_3^2 \text{Tr} \Delta^\dagger \Delta \\ & + \frac{1}{2} \lambda_1 (\Phi^\dagger \Phi)^2 + \frac{1}{2} \lambda_2 (\eta^\dagger \eta)^2 + \frac{1}{2} \lambda_3 (\text{Tr} \Delta^\dagger \Delta)^2 + \frac{1}{2} \lambda_4 (\text{Tr} \Delta^\dagger \Delta^\dagger) (\text{Tr} \Delta \Delta) \\ & + \lambda_5 (\Phi^\dagger \Phi) (\eta^\dagger \eta) + \lambda_6 (\Phi^\dagger \Phi) (\text{Tr} \Delta^\dagger \Delta) + \lambda_7 (\eta^\dagger \eta) (\text{Tr} \Delta^\dagger \Delta) \\ & + \lambda_8 (\Phi^\dagger \eta) (\eta^\dagger \Phi) + \lambda_9 (\Phi^\dagger \Delta^\dagger \Delta \Phi) + \lambda_{10} (\eta^\dagger \Delta^\dagger \Delta \eta) \\ & + \mu (\eta^\dagger \Delta \tilde{\eta}) + H.c., \end{aligned} \quad (5)$$

where  $\tilde{\eta} = (\tilde{\eta}^0, -\eta^-)$  and the parameter  $\mu$  has the dimension of mass. Lepton number is then assumed to be broken by explicit *soft* terms, i.e.

$$V_{\text{soft}} = \mu_{12}^2 \Phi^\dagger \eta + \mu' (\Phi^\dagger \Delta \tilde{\eta}) + \mu'' (\Phi^\dagger \Delta \tilde{\Phi}) + H.c. \quad (6)$$

Let  $\langle\phi^0\rangle = v_1$ ,  $\langle\eta^0\rangle = v_2$ , and  $\langle\xi^0\rangle = v_3$ , then the minimum of  $V$  is given by

$$\begin{aligned}
V_{min} &= m_1^2 v_1^2 + m_2^2 v_2^2 + m_3^2 v_3^2 + 2\mu_{12}^2 v_1 v_2 \\
&+ \frac{1}{2}\lambda_1 v_1^4 + \frac{1}{2}\lambda_2 v_2^4 + \frac{1}{2}\lambda_3 v_3^4 + (\lambda_5 + \lambda_8)v_1^2 v_2^2 + \lambda_6 v_1^2 v_3^2 + \lambda_7 v_2^2 v_3^2 \\
&+ 2\mu v_2^2 v_3 + 2\mu' v_1 v_2 v_3 + 2\mu'' v_1^2 v_3,
\end{aligned} \tag{7}$$

where  $\mu_{12}^2$ ,  $\mu$ ,  $\mu'$ , and  $\mu''$  have been assumed real for simplicity. The equations of constraint are obtained from  $\partial V_{min}/\partial v_i = 0$ , i.e.

$$v_1[m_1^2 + \lambda_1 v_1^2 + (\lambda_5 + \lambda_8)v_2^2 + \lambda_6 v_3^2 + 2\mu'' v_3] + \mu_{12}^2 v_2 + \mu' v_2 v_3 = 0, \tag{8}$$

$$v_2[m_2^2 + \lambda_2 v_2^2 + (\lambda_5 + \lambda_8)v_1^2 + \lambda_7 v_3^2 + 2\mu v_3] + \mu_{12}^2 v_1 + \mu' v_1 v_3 = 0, \tag{9}$$

$$v_3[m_3^2 + \lambda_3 v_3^2 + \lambda_6 v_1^2 + \lambda_7 v_2^2] + \mu v_2^2 + \mu' v_1 v_2 + \mu'' v_1^2 = 0. \tag{10}$$

Consider now the case  $m_1^2 < 0$ , but  $m_2^2 > 0$  and  $m_3^2 > 0$  with small  $\mu_{12}^2$ ,  $\mu'$  and  $\mu''$ . The solutions to the above equations are then

$$v_1^2 \simeq -\frac{m_1^2}{\lambda_1}, \tag{11}$$

$$v_2 \simeq -\frac{\mu_{12}^2 v_1}{m_2^2 + (\lambda_5 + \lambda_8)v_1^2}, \tag{12}$$

$$v_3 \simeq -\frac{\mu v_2^2 + \mu' v_1 v_2 + \mu'' v_1^2}{m_3^2 + \lambda_6 v_1^2}. \tag{13}$$

Since  $\mu'$  violates  $L$  by 1 unit and  $\mu''$  violates  $L$  by 2 units, it is reasonable to assume that  $\mu''/\mu' \sim \mu'/\mu \sim v_2/v_1$ . Thus for  $m_2$ ,  $m_3$ , and  $\mu$  all approximated by  $M \sim 1$  TeV,

$$v_2 \sim \frac{\mu_{12}^2 v_1}{M^2}, \quad v_3 \sim \frac{v_2^2}{M}. \tag{14}$$

This shows that  $v_3 \ll v_2 \ll v_1$ , and

$$v_3 \sim \frac{\mu_{12}^4 v_1^2}{M^5}, \tag{15}$$

i.e. the analog of Eq. (2). For  $v_1 \sim 10^2$  GeV and  $\mu_{12} \sim 1$  GeV, the solutions are  $v_2 \sim 0.1$  MeV and  $v_3 \sim 10^{-2}$  eV as desired.

In conclusion, a scenario has been presented where a Higgs triplet at the TeV scale is responsible for neutrino masses. The decay of  $\xi^{++}$  into  $l_i^+ l_j^+$  would then map out the neutrino mass matrix, as proposed previously [8]. In addition, a second Higgs doublet at the TeV scale is predicted [9] so that  $\xi^{++} \rightarrow \eta^+ \eta^+$  is also possible if kinematically allowed.

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